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Design of the Mu2e Straw Tracker Detector

New Perspectives 2017

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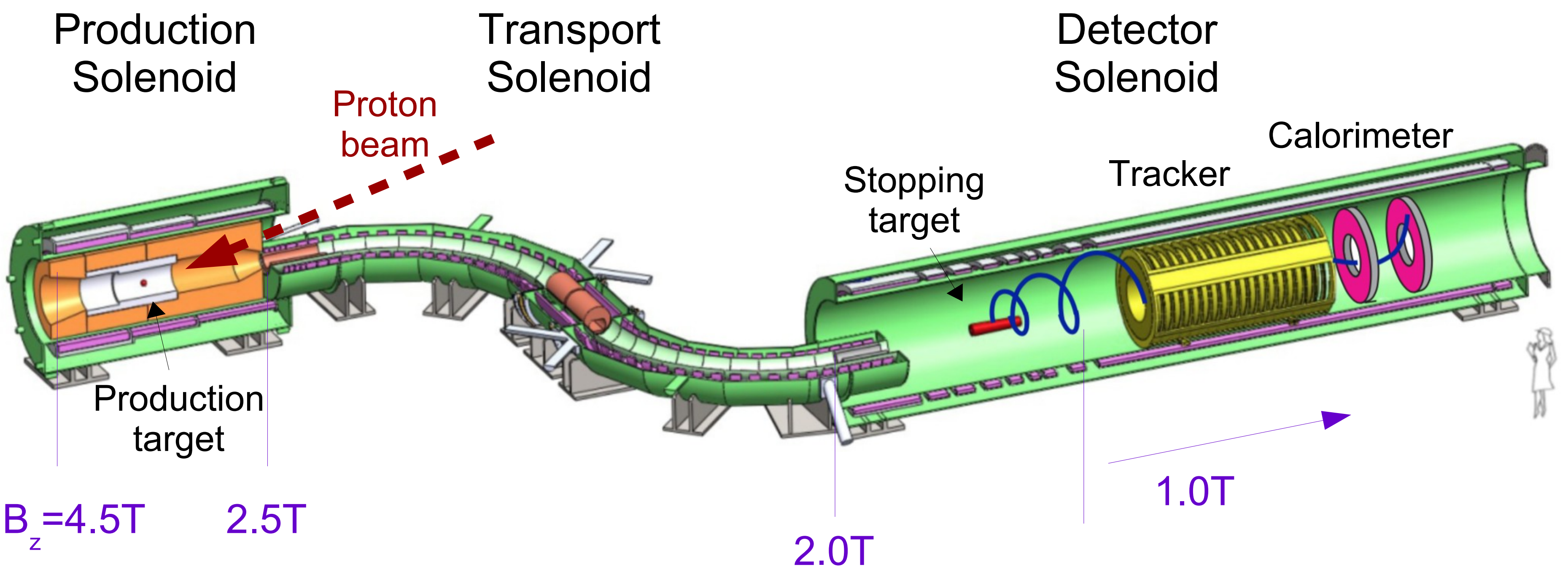
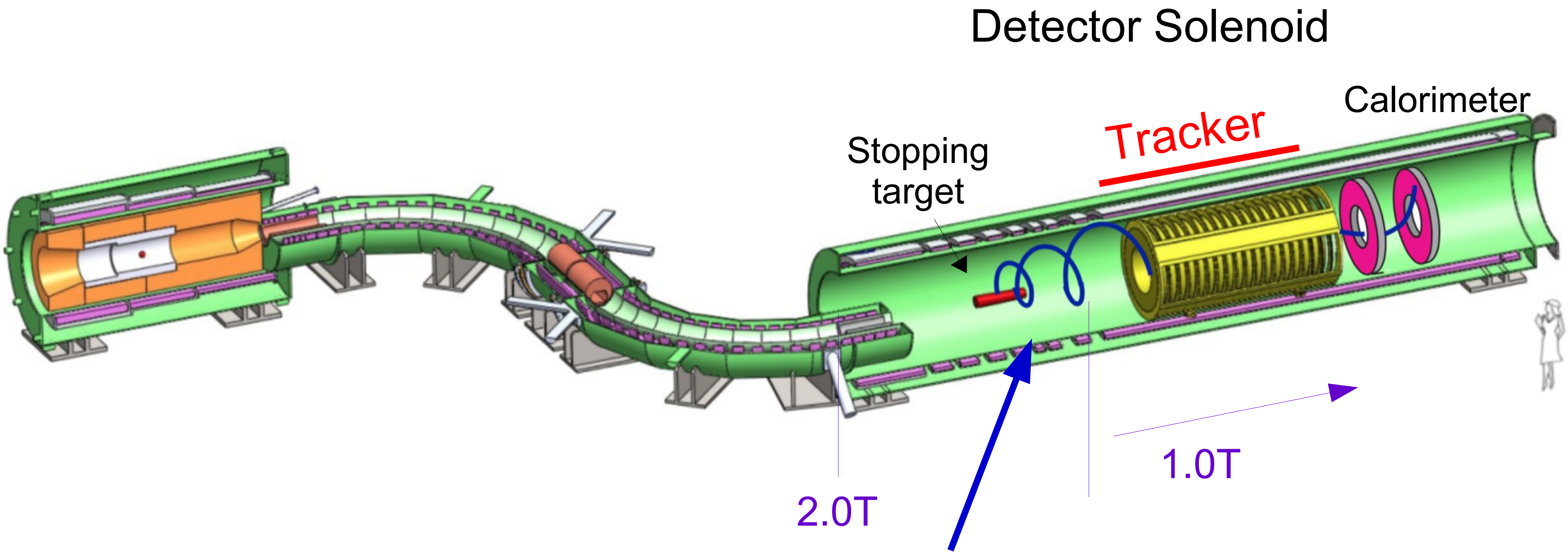
Mu2e in a Slide



- Experiment and apparatus just presented by J. Colston, *Mu2e in 10 minutes*
- Mu2e will search for signatures of Charged Lepton Flavor Violation
  - New Physics sensitivity up to mass scales of 10,000 GeV
  - A very important test to guide future of HEP theory and experiments
- Neutrino-less conversion of muon into electron in the field of Al nucleus.

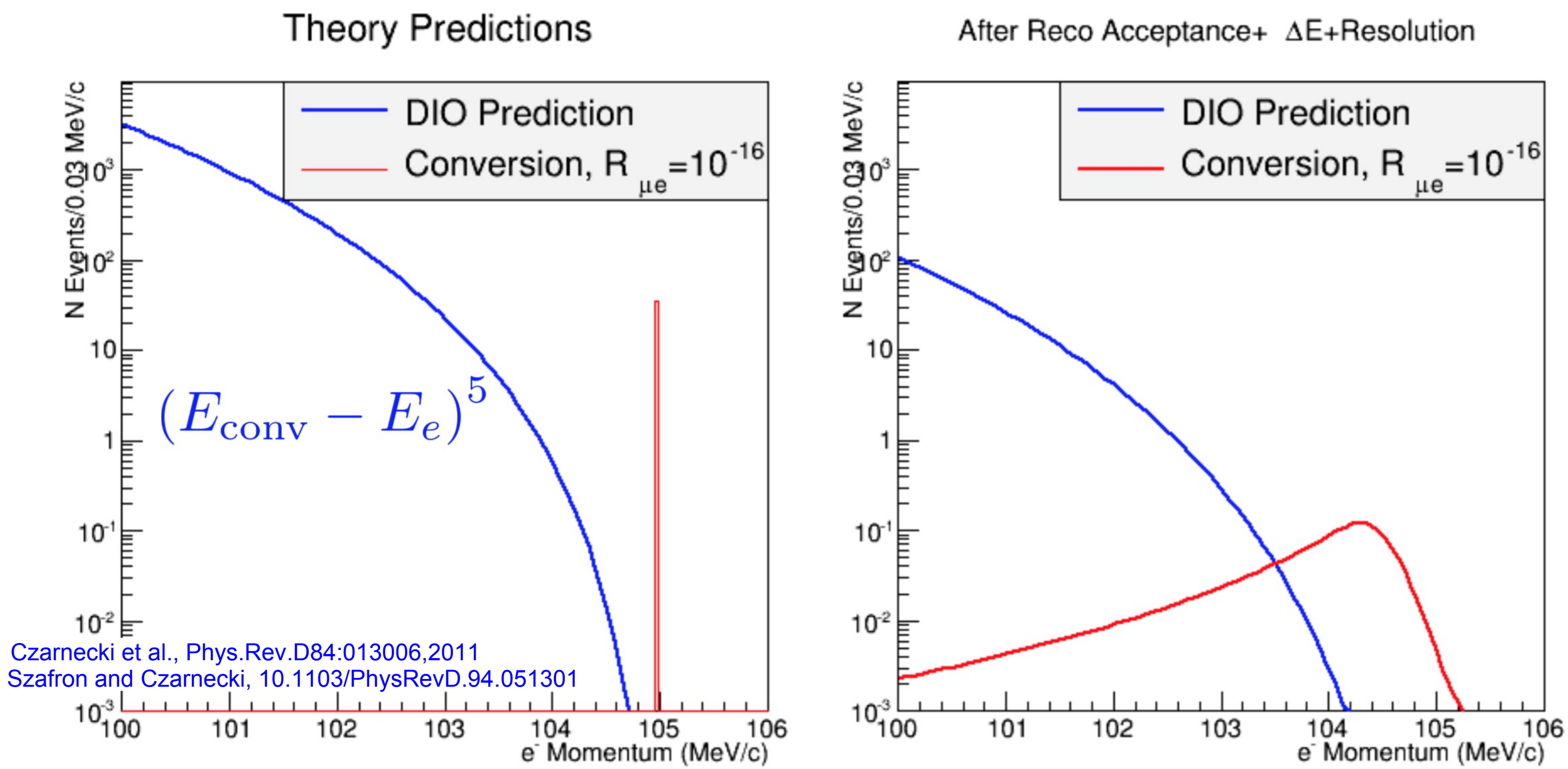
The Mu2e Tracker



- Characteristic signature of CLFV: 105 MeV conversion electron
  - Spiraling in helical orbit from Al stopping target

- The Mu2e Tracker: primary detector for the experiment.
  Designed to efficiently detect conversion electron and reconstruct trajectory
  - Required resolution 180 keV @ 105 MeV, or <0.18%
  - Operation in vacuum and in magnetic field
  - Must reject backgrounds from conventional processes

Background Process: Decay in Orbit



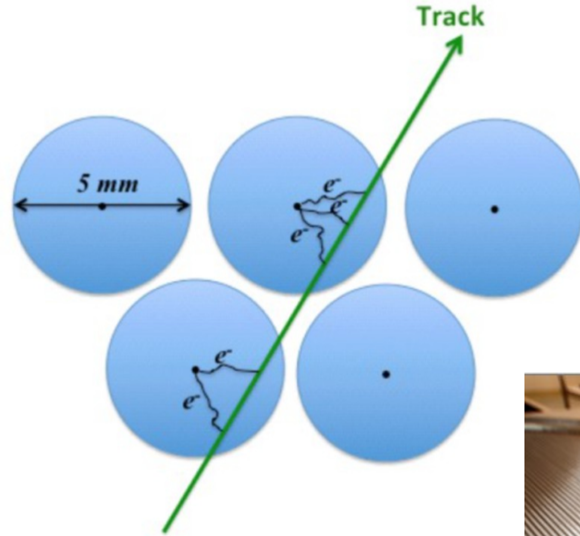
- Nuclear modification pushes decay-in-orbit (DIO) spectrum near conversion electron energy
- Overlap after energy loss in material and detector resolution

- DIO electrons only differ from signal through its momentum
  → Need low-mass detector with good resolution, especially on high side

Tracker Straw Tubes

Detecting element:
Gas drift tubes, or "straws"

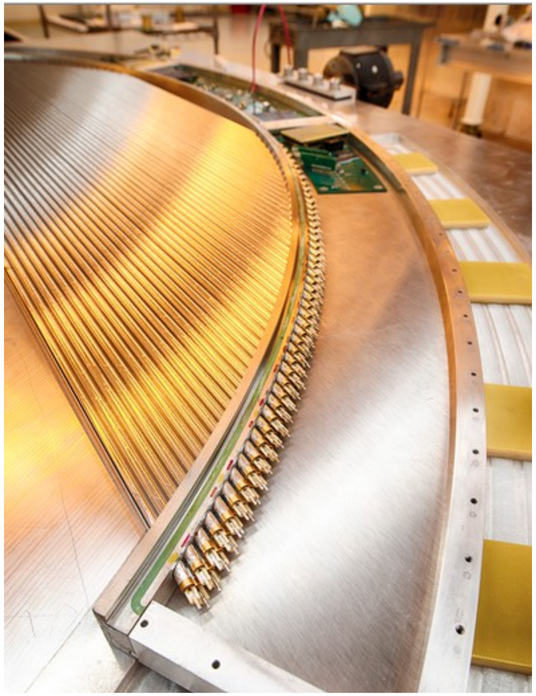
- 5mm diameter, 0.5-1.2m long
- 15µm mylar wall, metalized
- 25µm gold-plated tungsten wire at ~1450V
- Gas Ar:CO_2 80:20 at 1atm



Excellent fit to tracker requirements

- Low mass, minimize multiple scattering
- Highly segmented, handle high rates
- Operation in vacuum (10^{-4} Torr), straws must not leak
- Reliable – lifetime of 10 yrs, must operate for a full year without service

Minimal unit fully instrumented, including front-end electronics: 120° panel of 96 straws

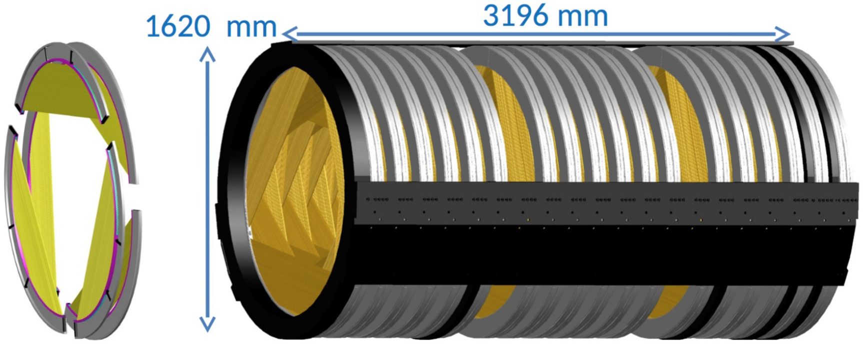


120° panel of 2x48 straws, two staggered layers

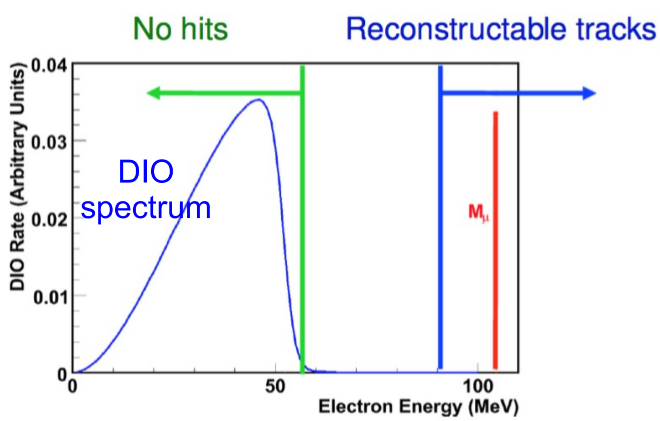
Tracker Annular Design

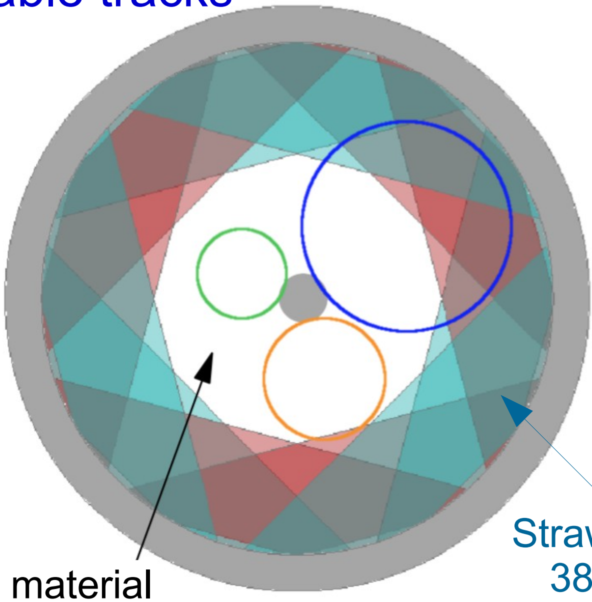
Panel unit is rotated and repeated, with hole in center.

- 12 panels per station, 18 stations
- Total 216 panels, ~21,000 straws
- 30º rotation for stereo reconstruction

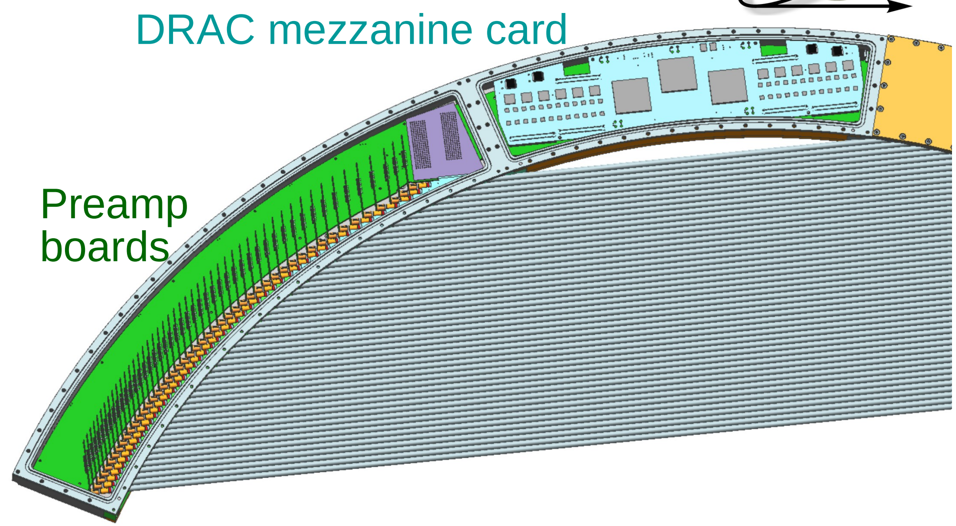


Annular design:
~97% of DIO electrons produce no hits
Tracker is blind to nearly all DIO background
Only electrons >90MeV have reconstructable tracks





Tracker Front-End Electronics



Front-End Electronics (FEE)

- Readout of straw signals
- Signal shaping and processing
- Digitization and transmission to DAQ

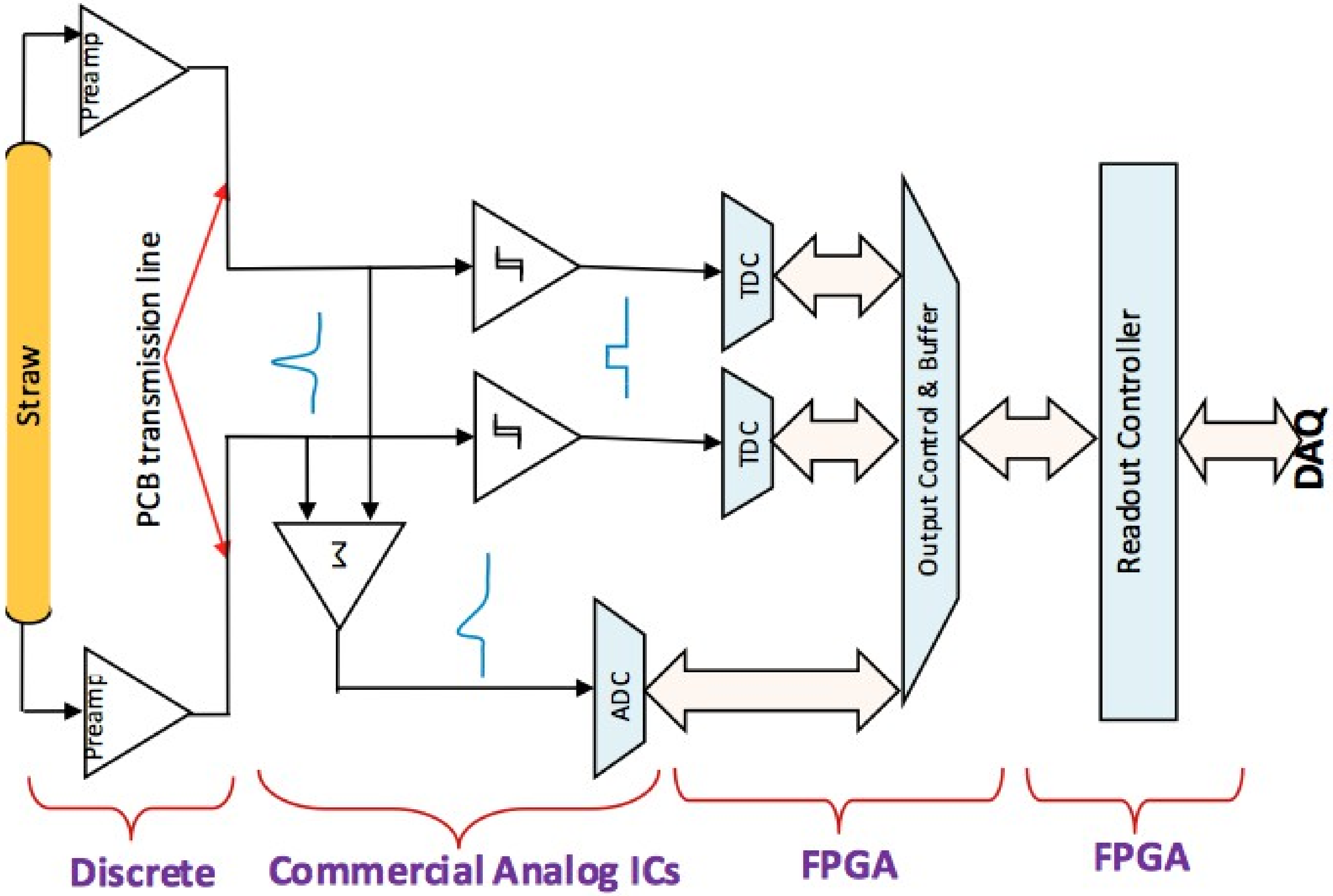
Requirements:

- Supply HV to straws (and capability for remote HV disconnect)
- B-field perturbation <1G in the active detector region
- Sustain radiation damage from target
- Low power <10kW within cooling capabilities
- $<12\times 96$ dead channels in 5 yrs at 90% CL

Measurements:

- TDC measurement of drift time – resolution: 2ns (<200μm drift radius)
- Straw readout from both ends for time division measurement
  – yields hit position along straw axis, <4cm resolution
- ADC for dE/dx measurement to identify highly-ionizing proton hits

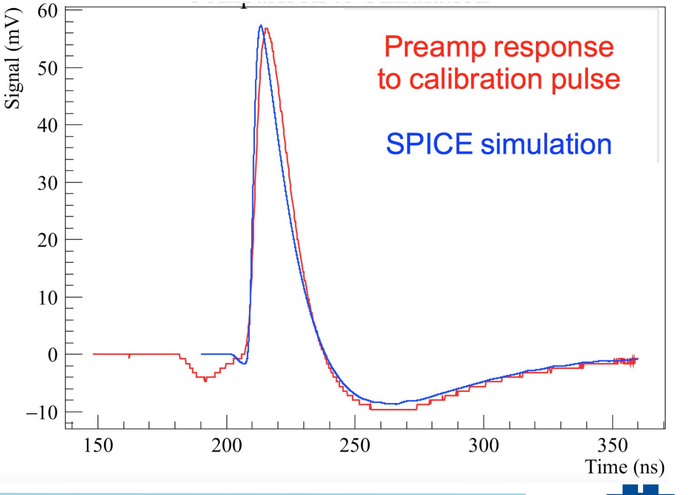
FEE Design



Preamp
Straw
PCB transmission line
Preamp
TDC
TDC
ADC
Σ
Output Control & Buffer
Readout Controller
DAQ
Discrete
Commercial Analog ICs
FPGA
FPGA

Preamplifier and Shaper

- 2- channel preamp boards connecting to straws, mounted on analog motherboard
- Straw signal readout
  - Low-noise high-speed input stage
  - SiGe technology BJT
  - Active 300Ω termination to avoid reflections
  - Differential output for good CMRR
- Provide HV and ground to straws
  - Remote disconnect from HV via thermal fuse
- Shaping of straw signal before digitization
  - Fast rise, long tail from ion motion
- Calibration system mimics e- pulse



Digitization and Readout

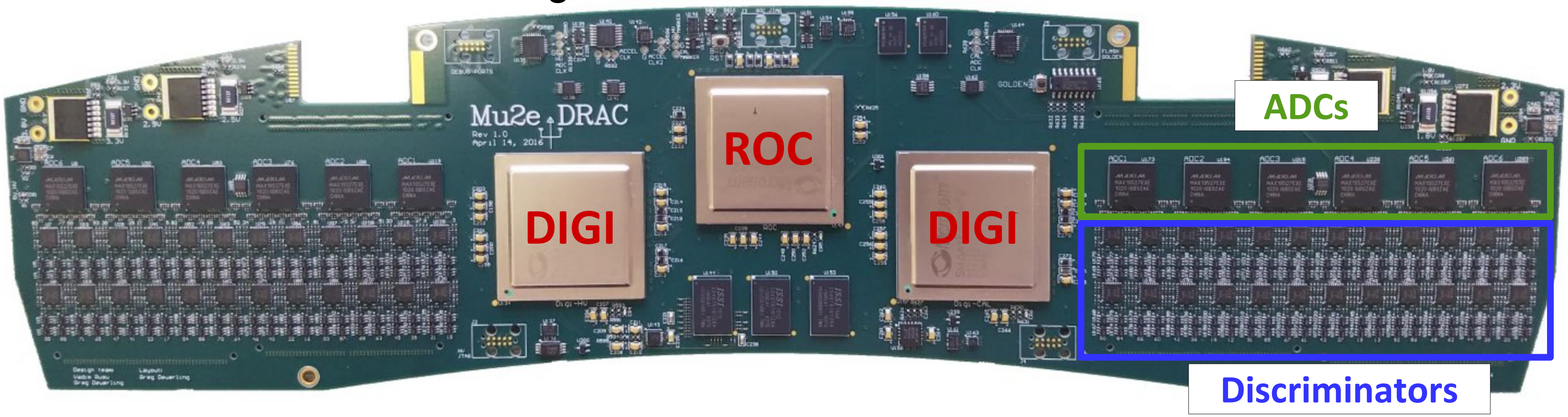
All signals routed to DRAC – Digitizer Readout Assembler and Controller
- Serves entire panel (2 × 96 TDCs and 96 ADCs)

Digitization

Each straw end goes into comparator and TDC (implemented in FPGA)
Two ends are analog summed and into 12-bit ADC, sampling at 50MHz
Data packaged (FPGA) and sent to ROC

Readout

Receives and buffers data from digitizer FPGAs
Duplex optical communication to DAQ
Panel control and monitoring

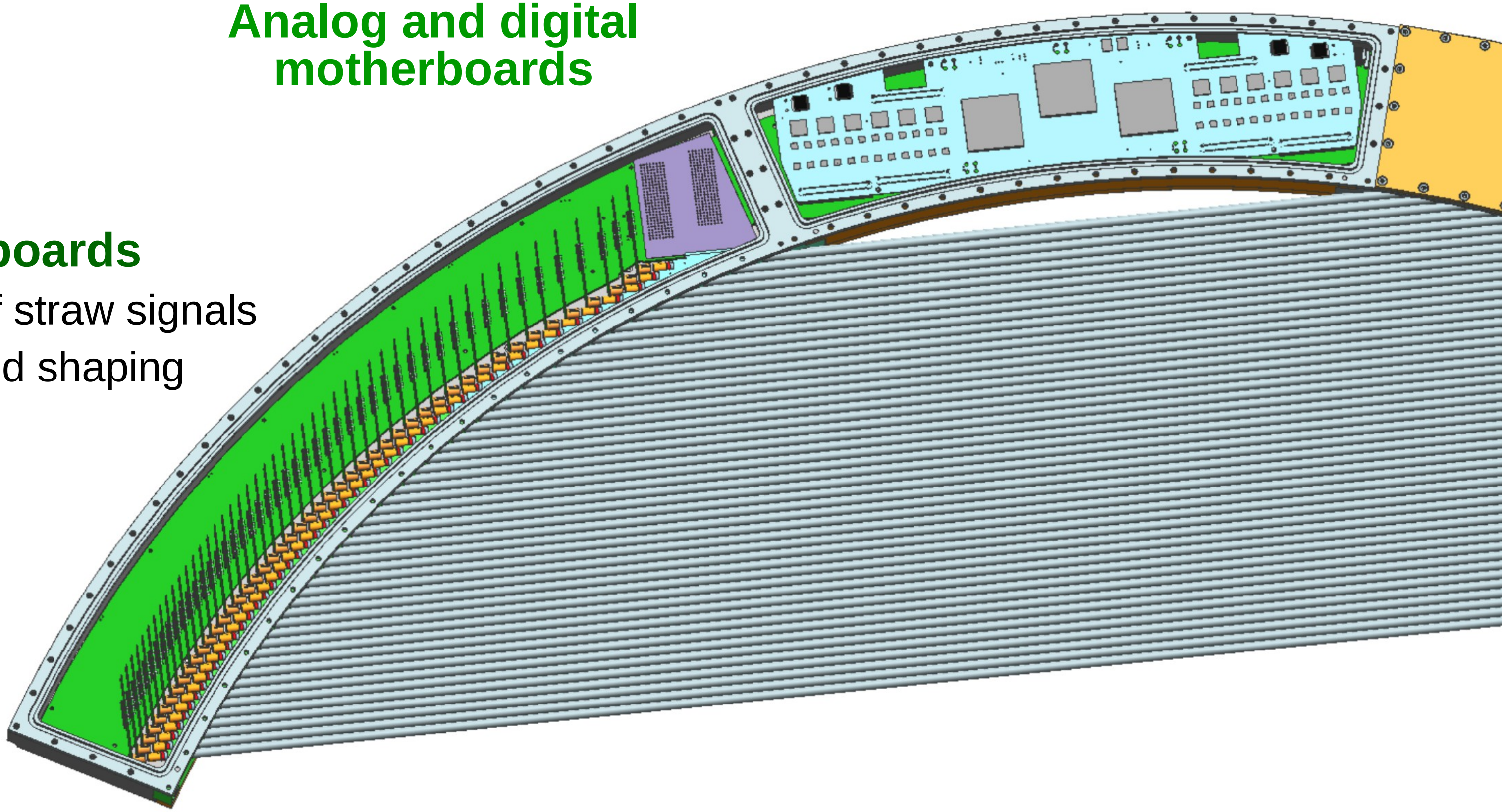


Summary: FEE Components

DRAC mezzanine card
Digitization and ROC

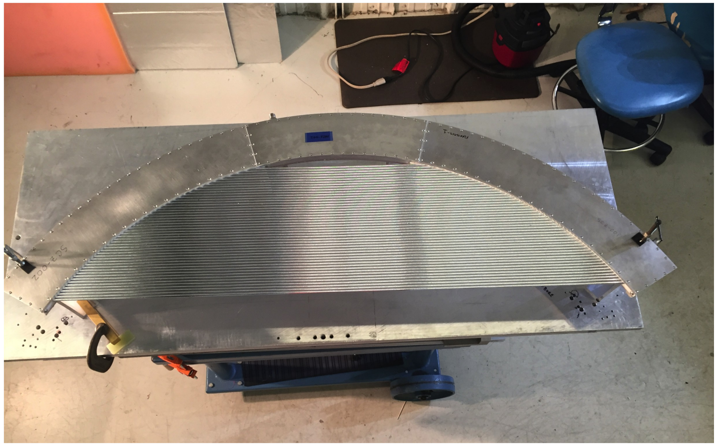
Analog and digital motherboards

Preamp boards
Readout of straw signals
Preamp and shaping

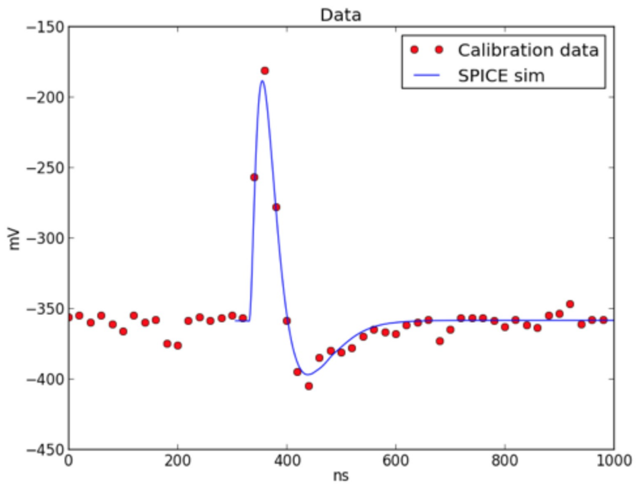


Status/Outlook

- Latest panel prototype recently constructed and being tested
- FEE prototypes created and tested successfully. FPGA firmware under development, but functionality has been shown.
- Vertical slice test to be performed on fully instrumented panels with entire FEE chain
  - Ground loops, noise, crosstalk
- Detector installation in 2020, followed by Mu2e commissioning and data!



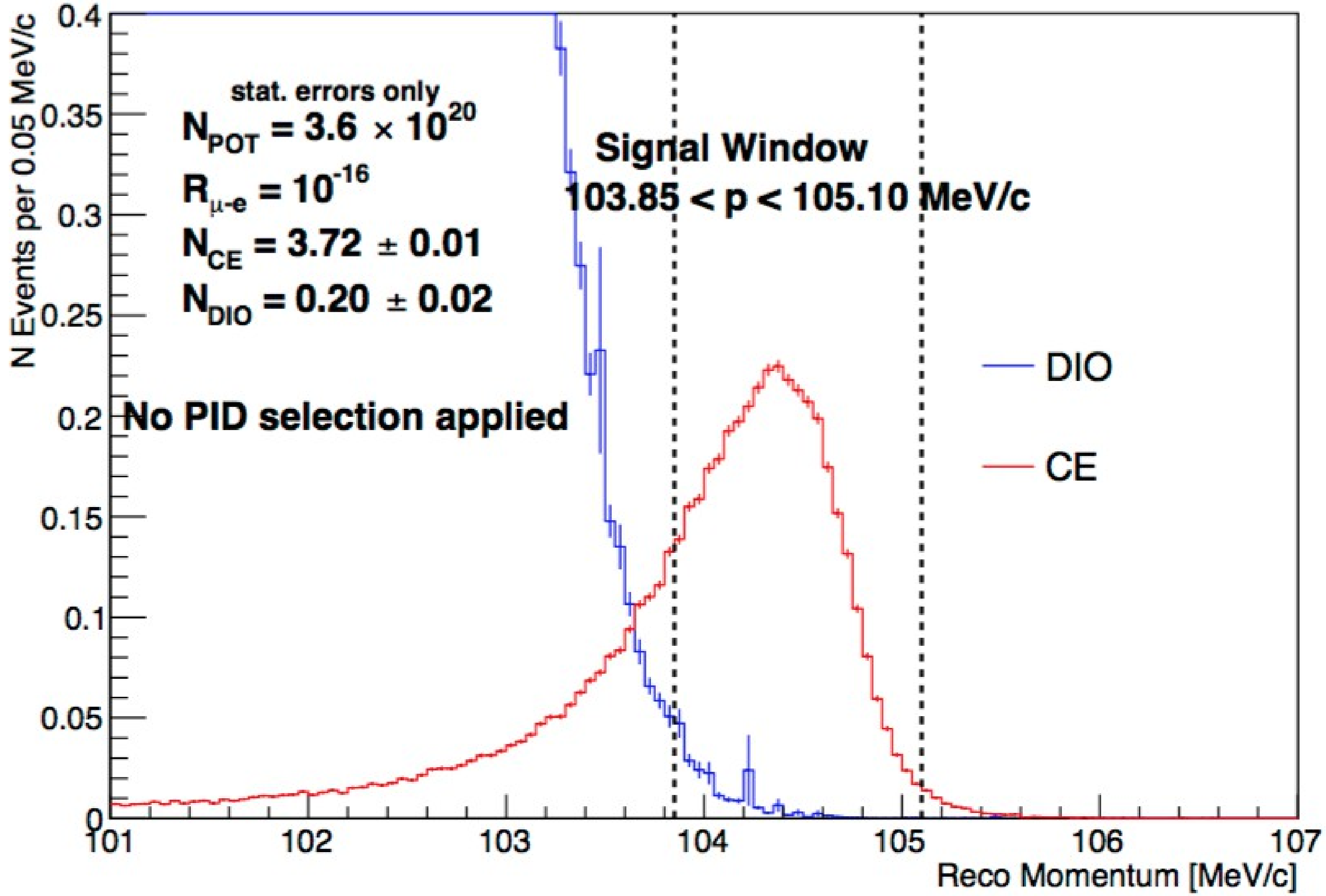
Latest Tracker panel prototype



ADC samples from calibration pulse read out from DRAC

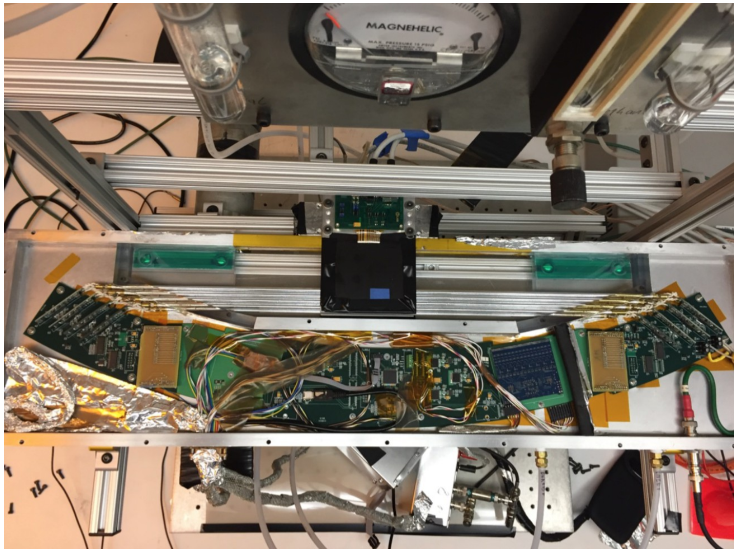
Backup

Signal and DIO Background



For $R_{\mu e} \approx 10^{-16}$ we expect to see ~4 conversion events without background contamination

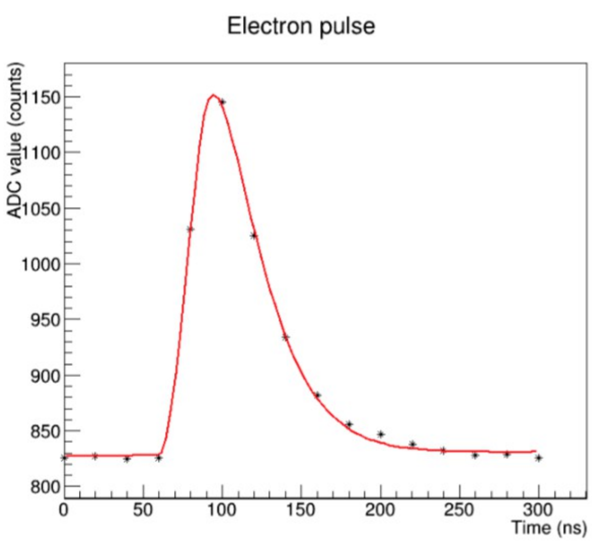
Small-scale prototype

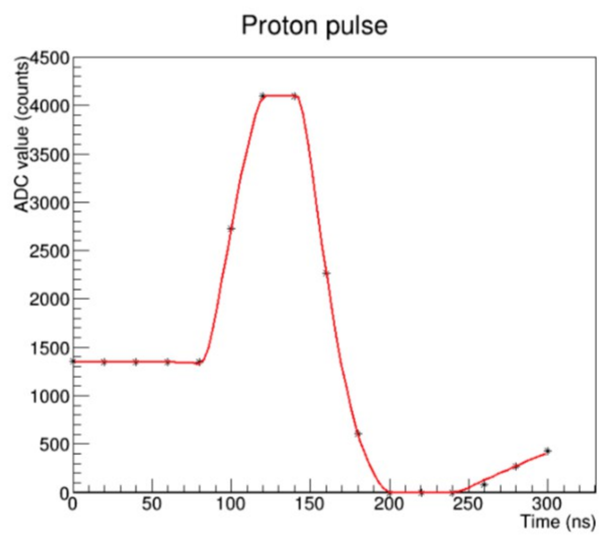


FEE chain tested in 8-channel prototype.

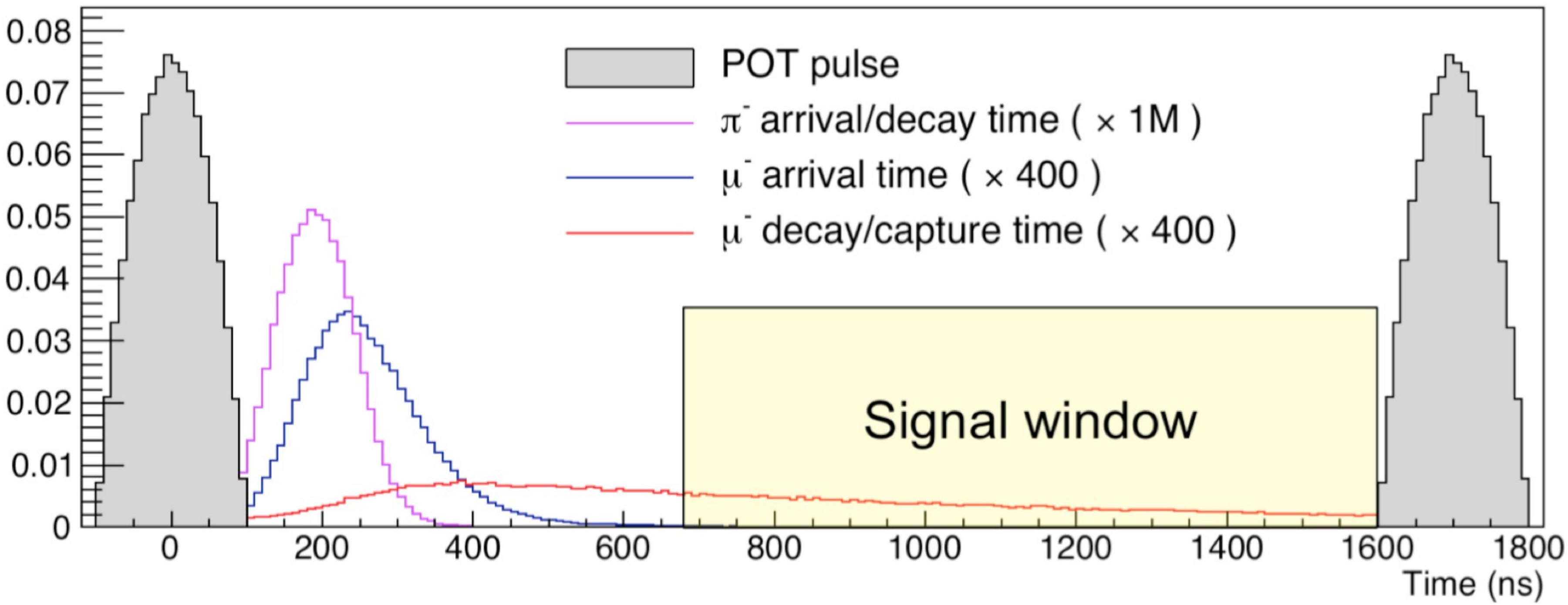
ADC output from electron and proton pulses shown below.

Preamp saturation allows identification of proton hits.





Pulsed Beam and Delayed Signal Window



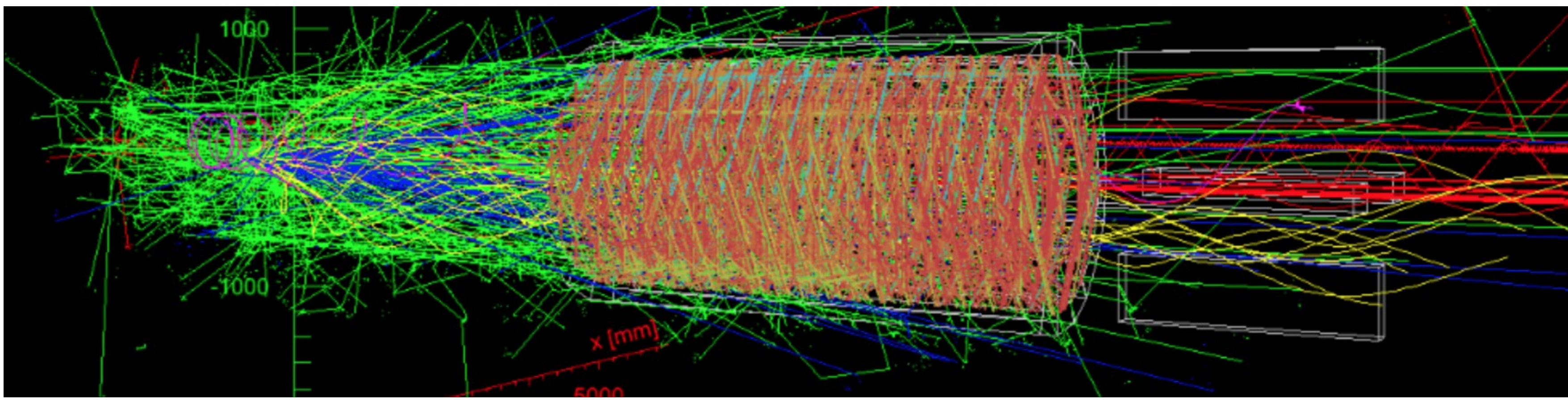
- Proton pulse period: 1695 ns (FNAL Delivery Ring)
- Delayed signal window: 700 → 1600 ns
- Pion lifetime: 26 ns – prompt backgrounds decay before signal window
- Muonic Al lifetime: 864 ns – reason for selecting Al target

Require beam extinction (fraction of beam between pulses): $\varepsilon < 10^{-10}$

Tracking

From individual straw hits in tracker we need to:

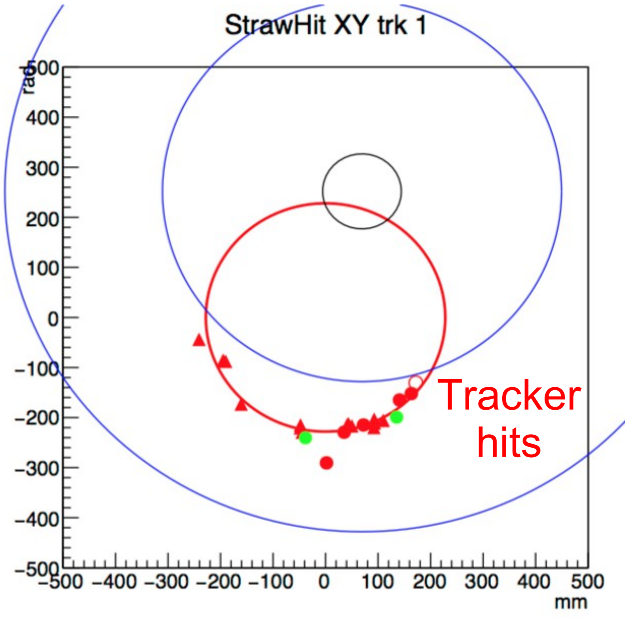
- Remove background hits
- Identify hits from single particle (pattern recognition)
- Reconstruct particle's trajectory (helix fitting)

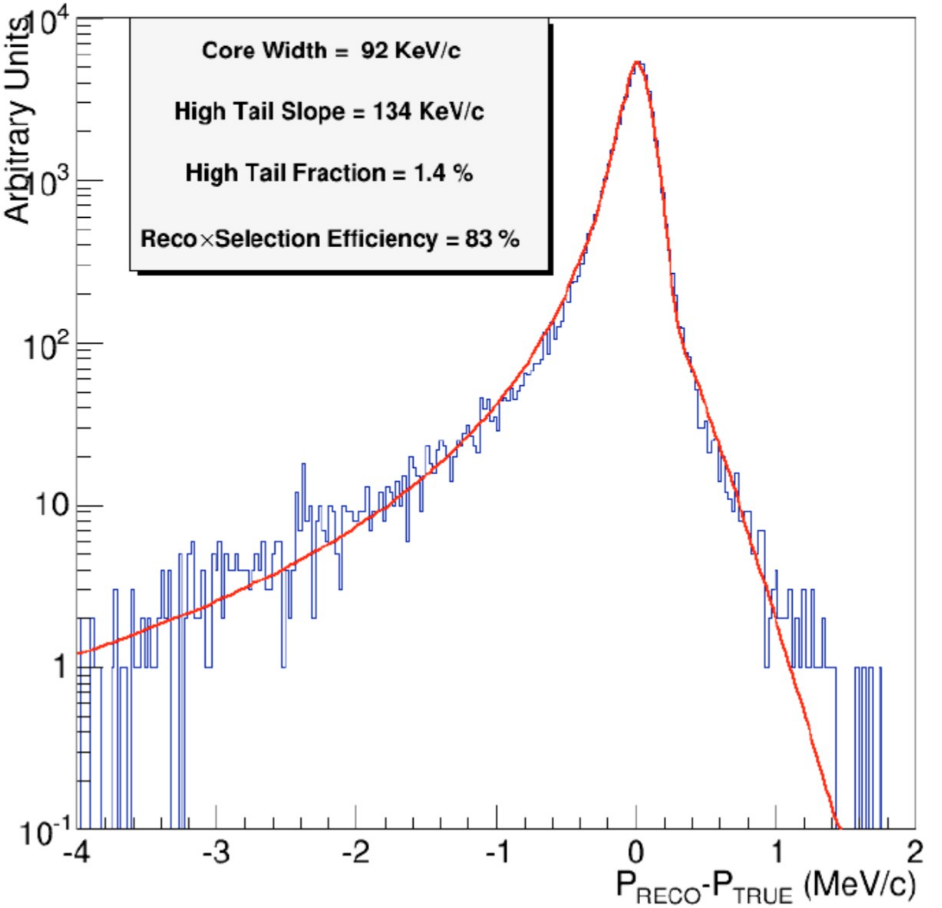


Signal electron + all hits over 500-1695 ns window

Detailed G4 model: straws, electronics, supports, B-fields

Tracker Momentum Resolution

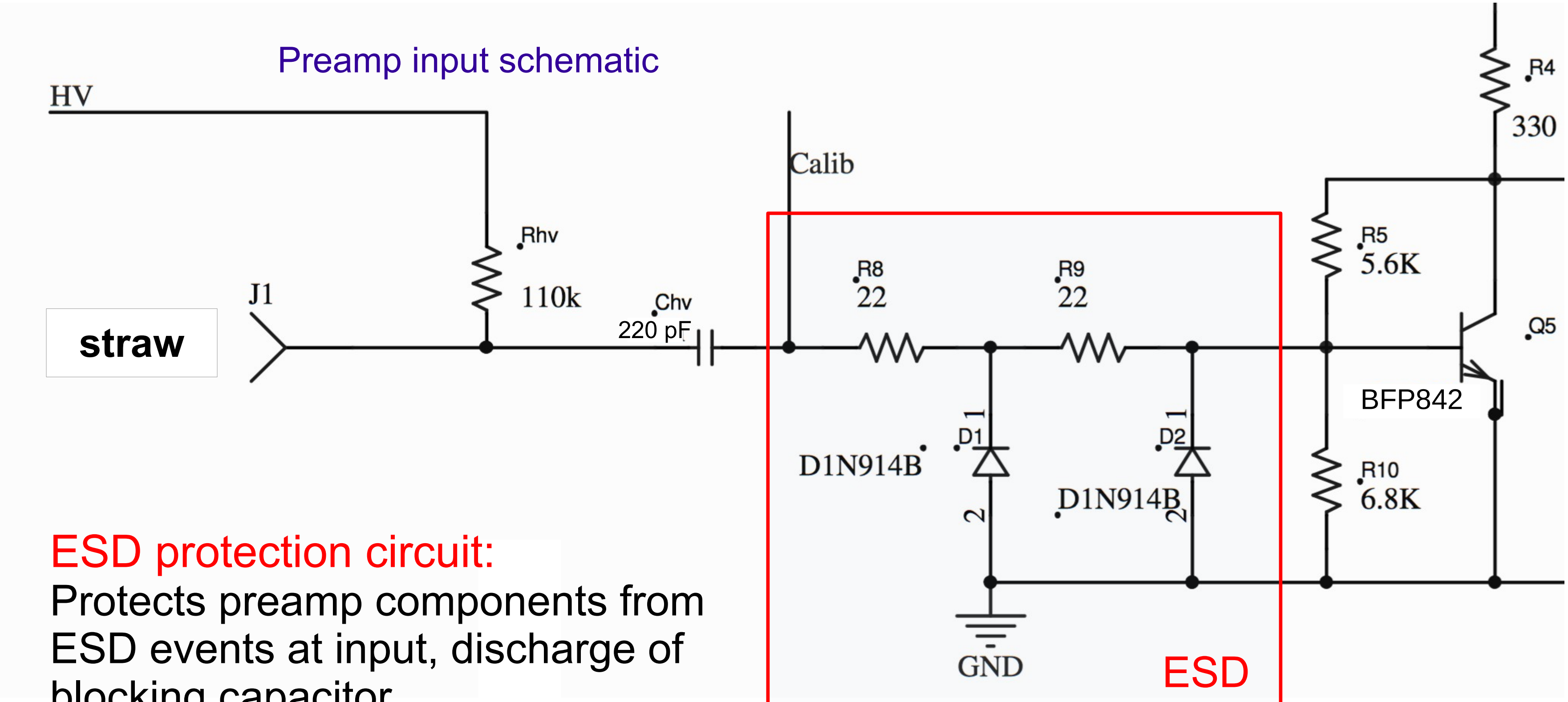




Least squares helix fit, followed by iterative Kalman Filter track fit

Tracker momentum resolution requirement:
σ_p/p<0.2% for a 105 MeV electron, or σ_p<180 keV/c

Preamp ESD protection



ESD protection circuit:
Protects preamp components from ESD events at input, discharge of blocking capacitor.

R8,R9: Current-limiting resistors. Input resistance contributes to thermal noise.
D1,D2: Diodes for ESD protection, shunt to ground on overvoltage. Capacitance limits BW.
Q5: 1st stage BJT to be protected, Infineon BFP842.